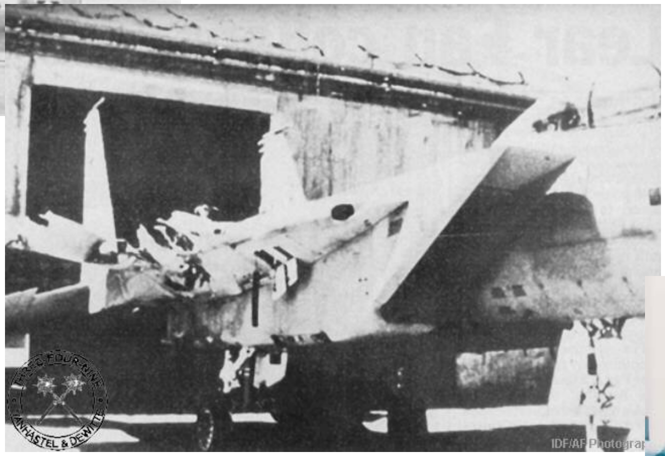
Full-Scale Flight Research Testbeds

Adaptive and Intelligent Control

Motivation for Adaptive Control

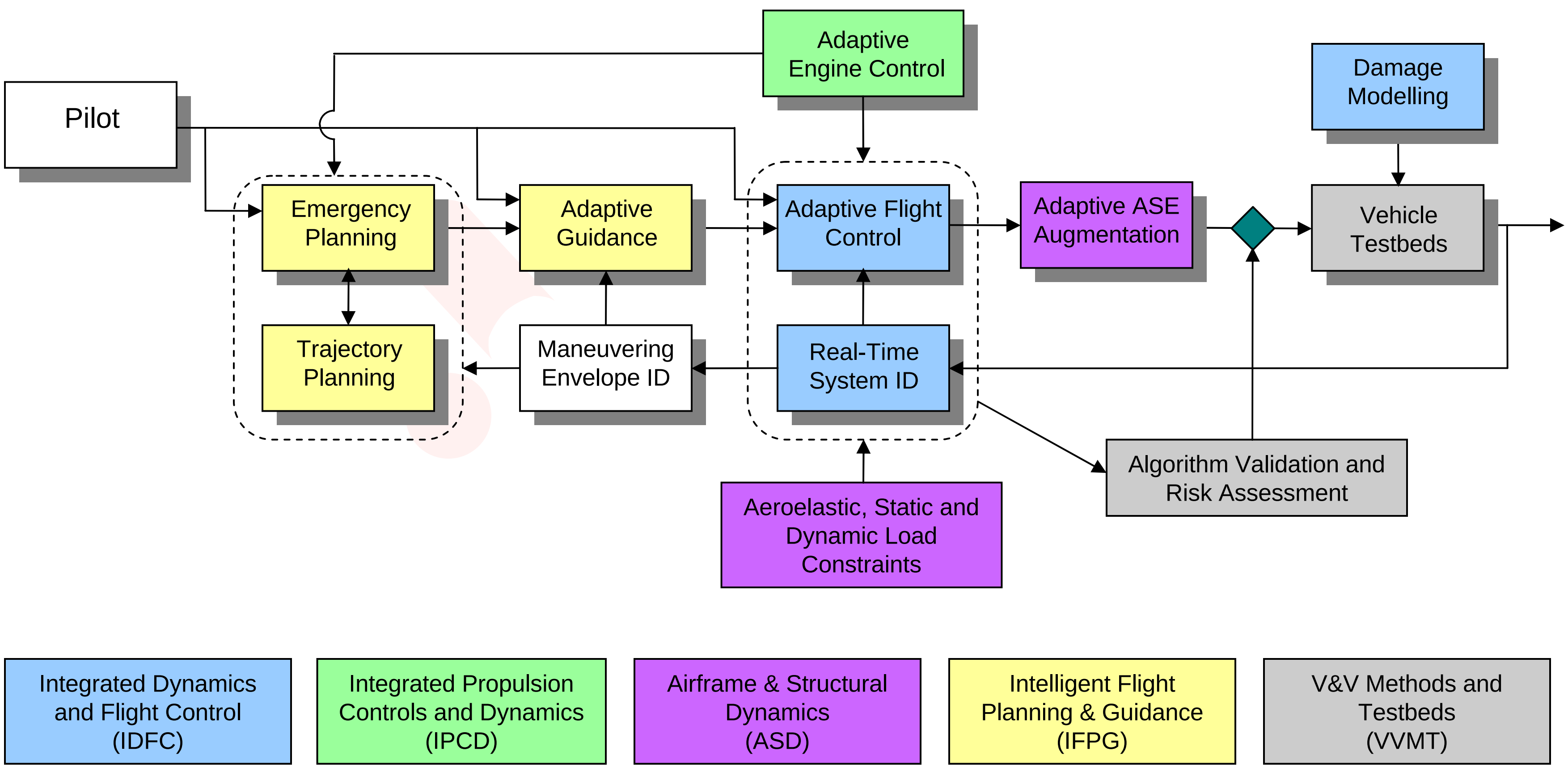


These are survivable accidents

Adaptive or Intelligent control has potential to reduce the amount of skill and luck required for survival

Integrated Resilient Aircraft Control Project

"Stability, maneuverability, and safe landing in the presence of adverse conditions"



Full-scale Flight Assets in Use for IRAC

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC03–0039–1 Date: February 7, 2003 Photo By: Jim Ross

NASA Dryden's highly–modified Active Aeroelastic Wing F/A–18A shows off its form during a 360–degree aileron roll during a research flight.

F/A-18 T/N 853

Flight validated sim

68040 RFCS

S/W tools available in-house

HIL test bench at NASA

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC03–0311–05 Date: December 4, 2003 Photo By: Jim Ross

C–17 in flight over Rogers Dry lakebed

C-17 T1 (USAF asset)

Primarily engine instrumentation

Dryden Flight Research Center EC96-43780-1 Photographed 10/96
Striking Silhouette: F-15B Advanced Control Technology for Integrated Vehicles (ACTIVE) research program. NASA photo by Jim Ross

F-15 837

Flight validated sim

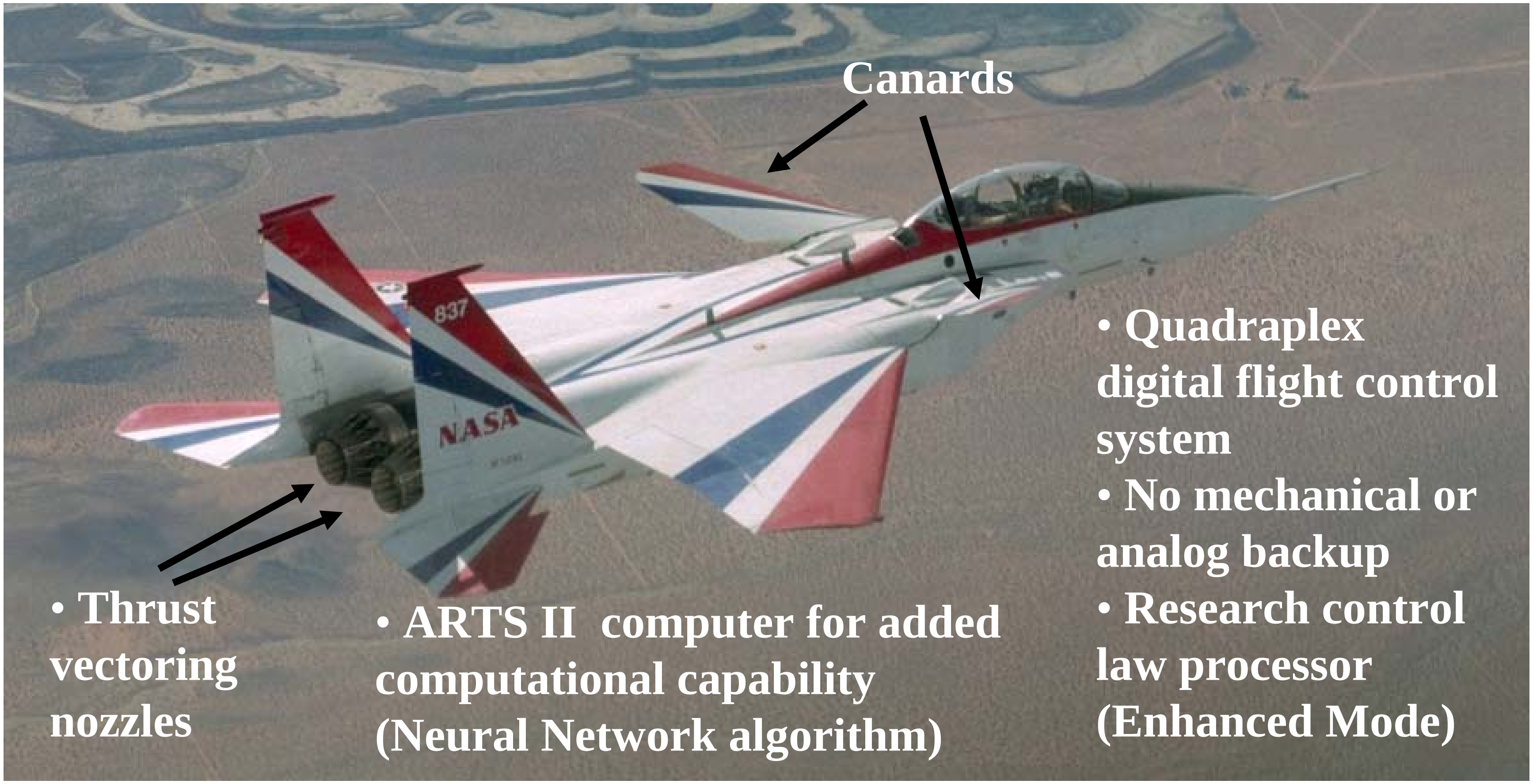
68040 enhanced mode

ARTS II (ISR)

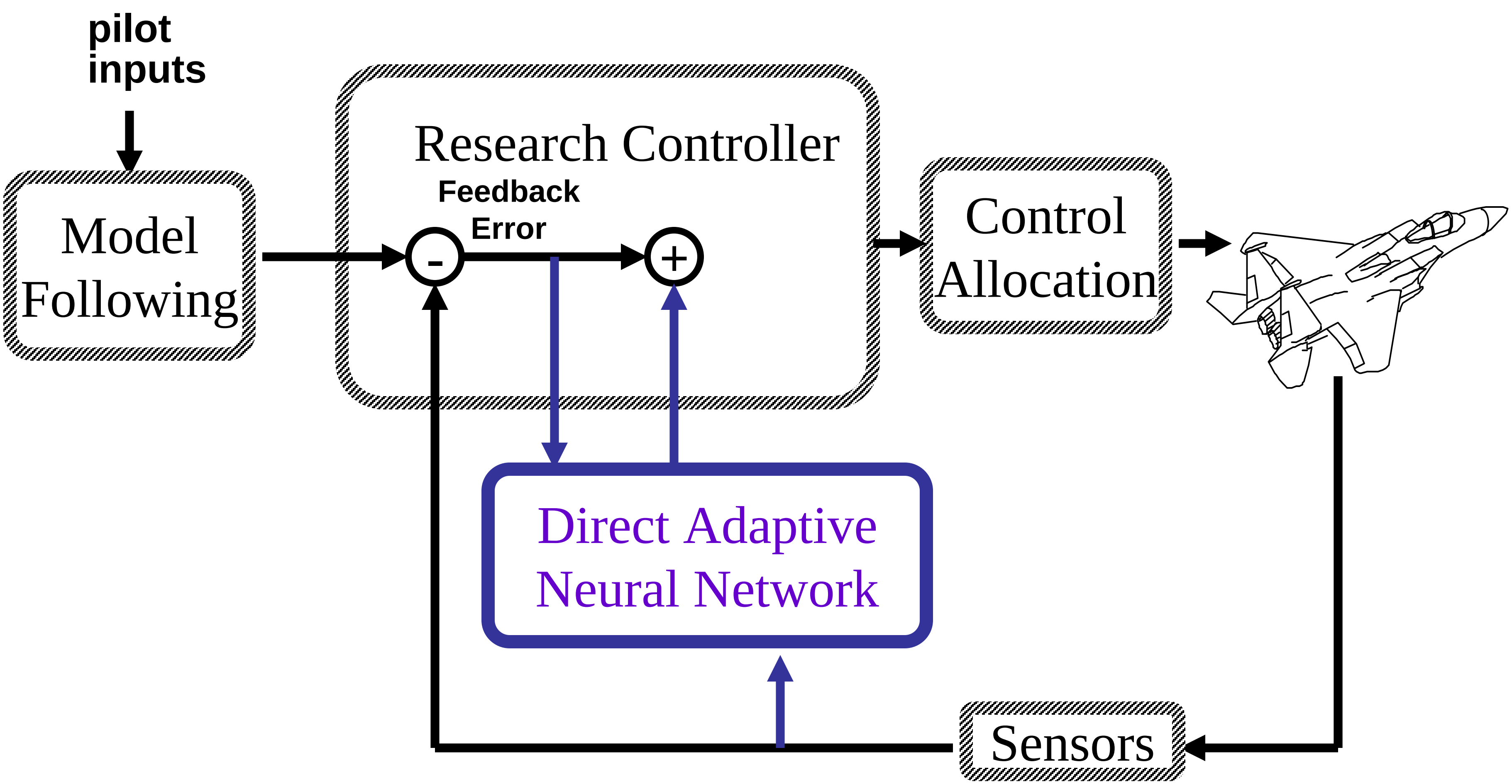
HIL at Boeing

NASA NF-15B Tail Number 837

Extensively modified F-15 airframe

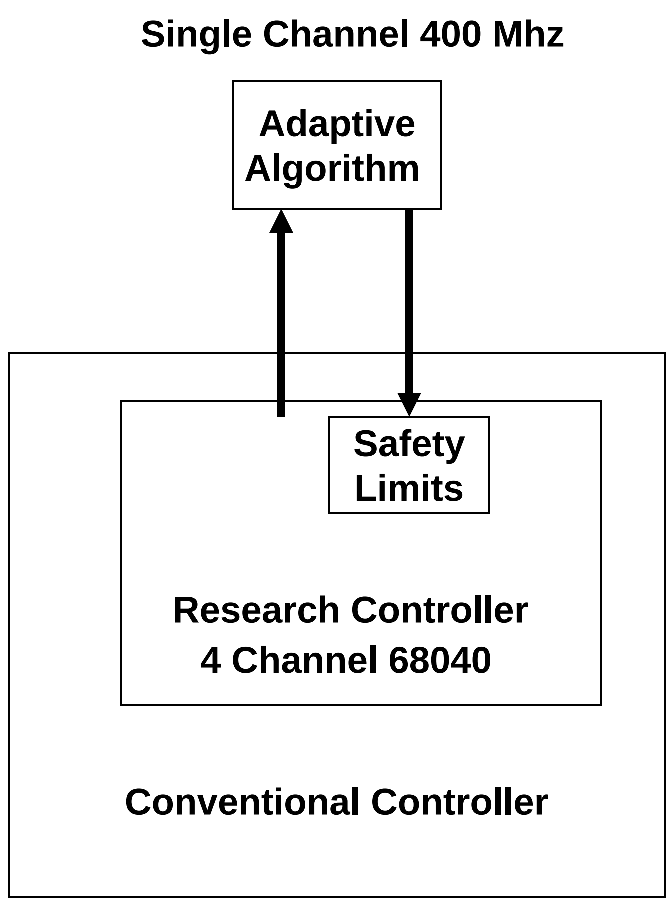


Gen II Direct Adaptive Control Architecture



Limited Authority System

- Adaptation algorithm implemented in separate processor
  - Class B software
  - Autocoded directly from Simulink block diagram
  - Many configurable settings
    - Learning rates
    - Weight limits
    - Thresholds, etc.
- Control laws programmed in Class A, quad-redundant system
- Protection provided by floating limiter on adaptation signals

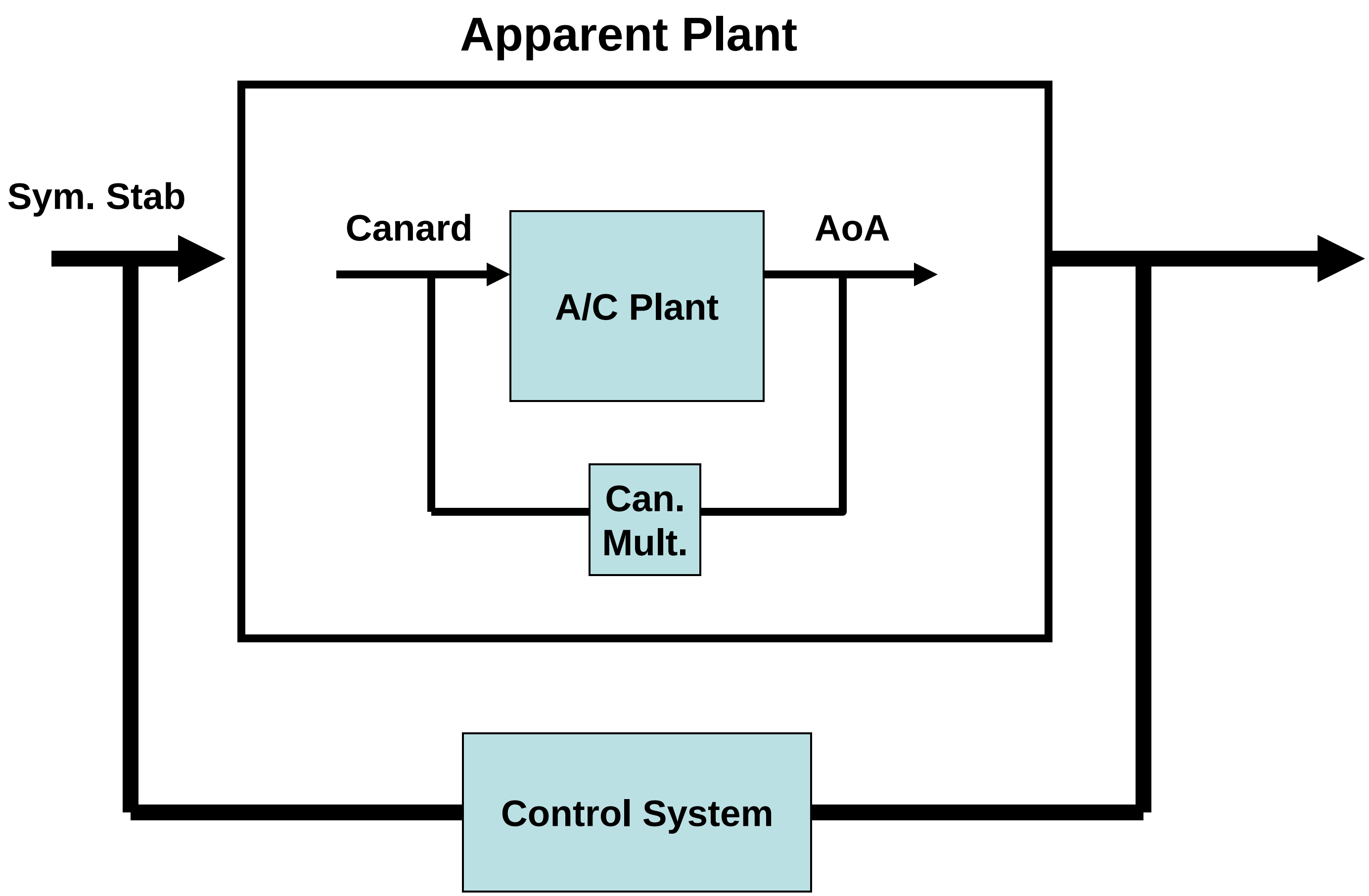


837 Flight Experiments

- Assess handling qualities of Gen II controller without adaptation
- Activate adaptation and assess changes in handling qualities
- Introduce simulated failures
  - Control surface locked (“B matrix failure”)
  - Angle of attack to canard feedback gain change (“A matrix failure”)
- Re-assess handling qualities with simulated failures and adaptation.
- Report on “Real World” experience with a neural network based flight control system

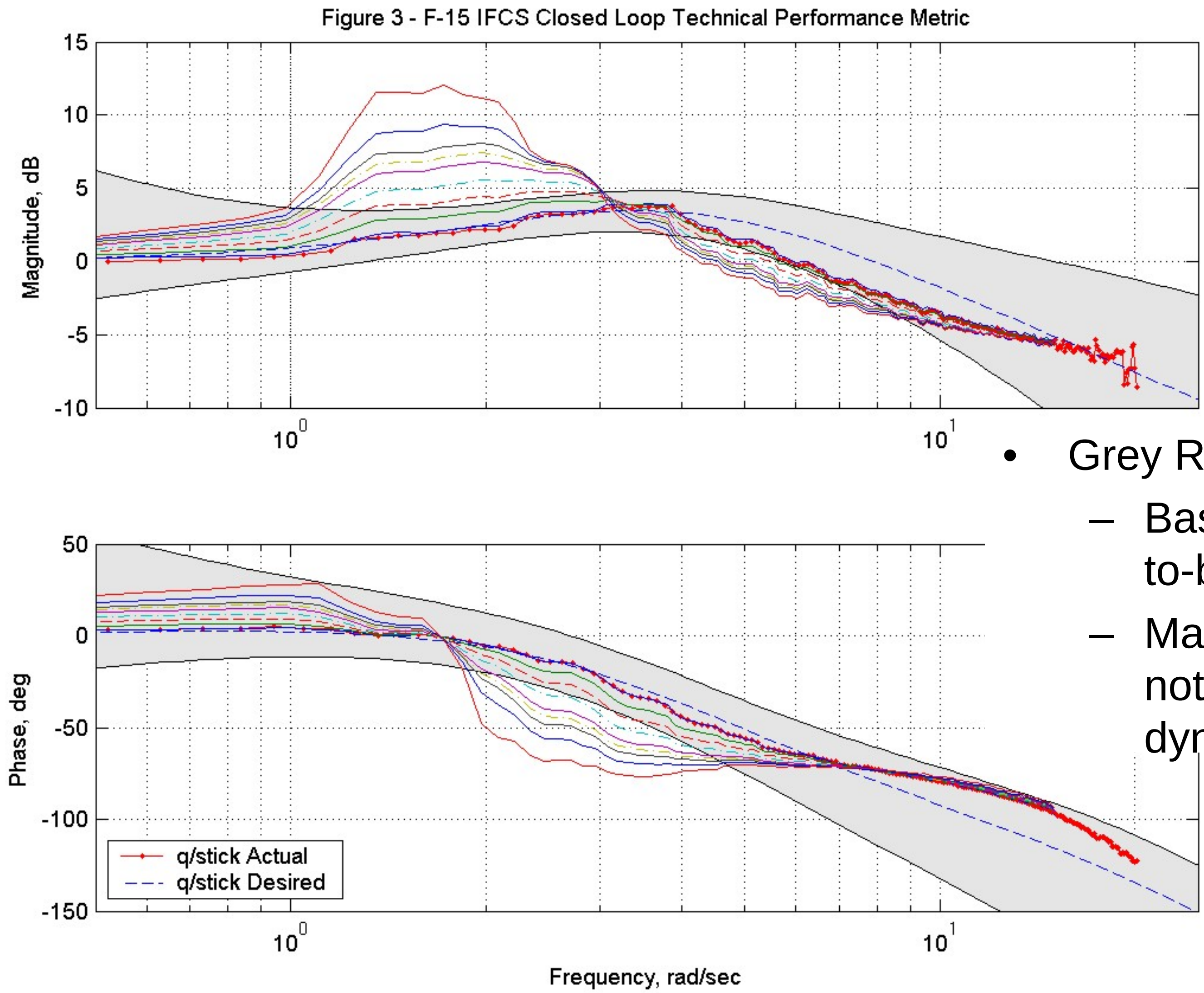
Simulated Destabilization
A-Matrix Failure

Effect of Canard Multiplier



Canard Multiplier Effect

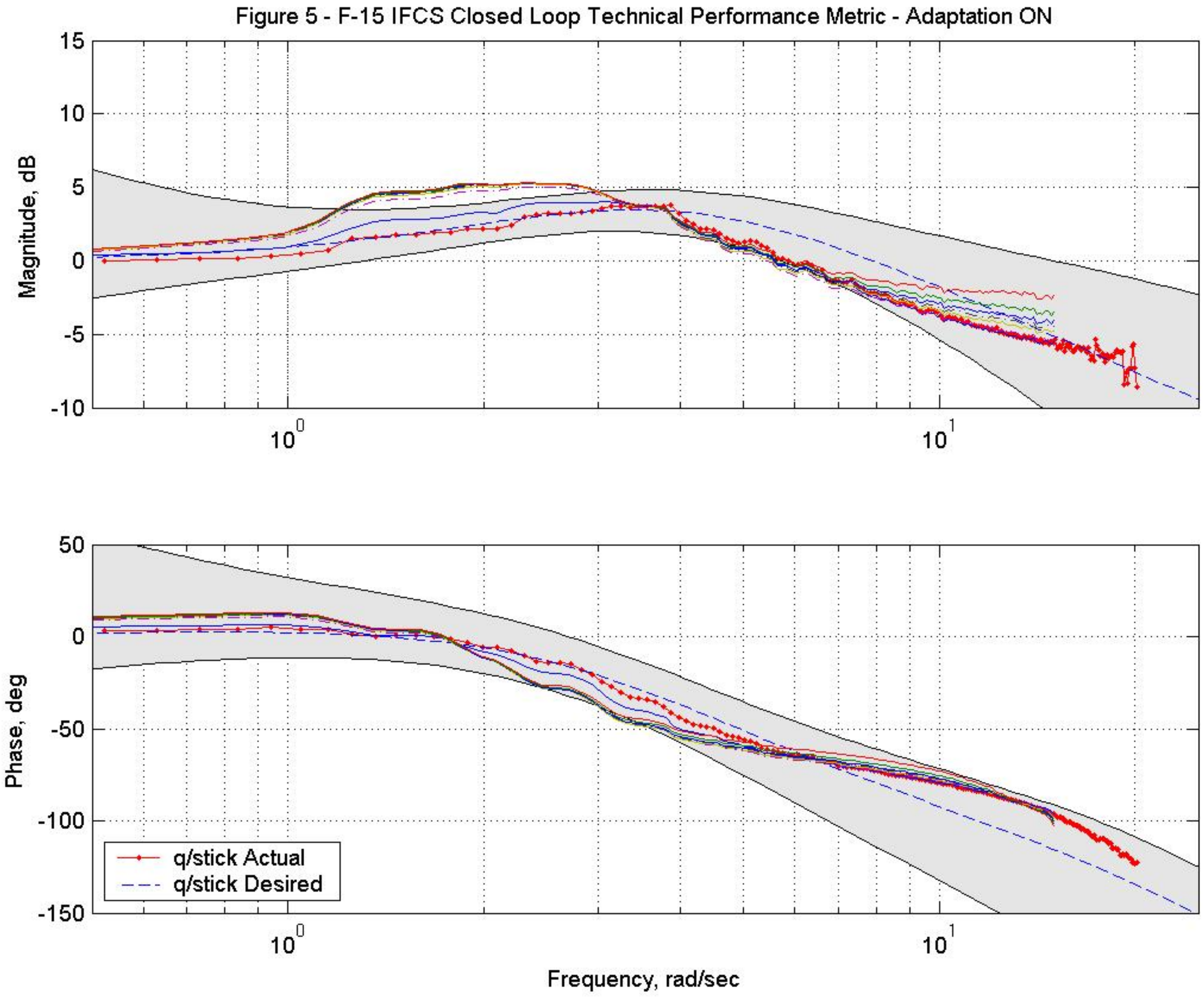
Closed Loop without Adaptation



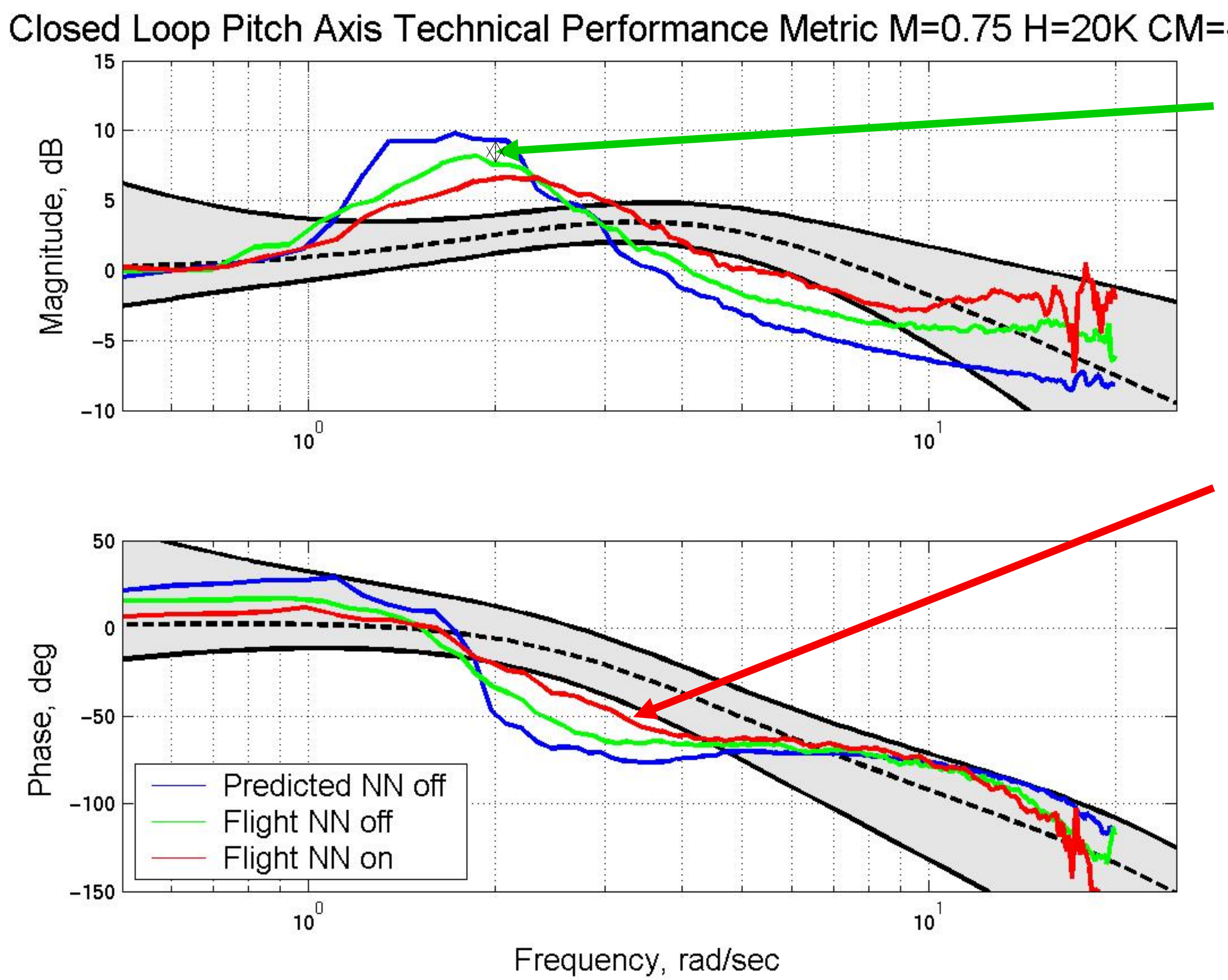
- Grey Region:
  - Based on model-to-be-followed
  - Maximum noticeable dynamics (LOES)

Canard Multiplier Effect

Closed Loop with Adaptation



Simulated Destabilization Failure



- **Flight Results of simulated failure less than predicted**
- **Adaptation Improved response**
- **Software change in work to increase failure size**

Conclusions

- Adaptive system generally behaved as predicted
  - Weights adjusted in correct direction
  - Real world turbulence and measurement noise did not adversely affect adaptation
  - Only safety disengagements observed were due to very aggressive pilot inputs

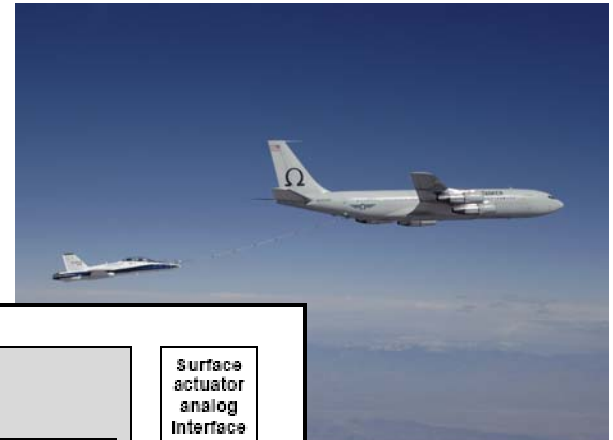
- Simulated destabilization less than predicted
  - Flight vehicle more stable than aero model predicts
  - Software change in work to increase destabilizing gain

- No metrics currently exist for damaged vehicles

- Gained valuable real world experience that has already pushed technology to more acceptable level

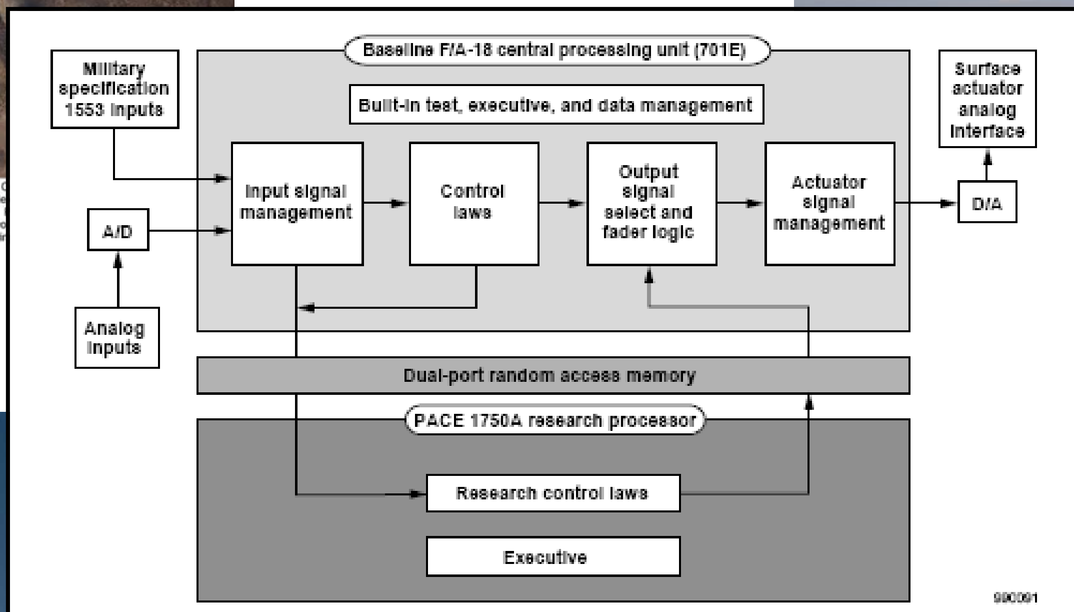
F/A-18 RFCS Architecture – a 20 Year Legacy

NASA Dryden Flight Research Center Photo C
http://www.dfrc.nasa.gov/gallery/photo/inde
NASA Photo: EC01-0328-12 Date: November 9, 2001
Smoke generators show the twisting paths of wingtip vortices behind two
Autonomous Formation Flight (AFF) program durin



arch Center Photo Collection
/Gallery/Photo/index.html
October 25, 2005 Photo By: Jim Ross

n Autonomous Airborne Refueling Demonstration
D) flight.



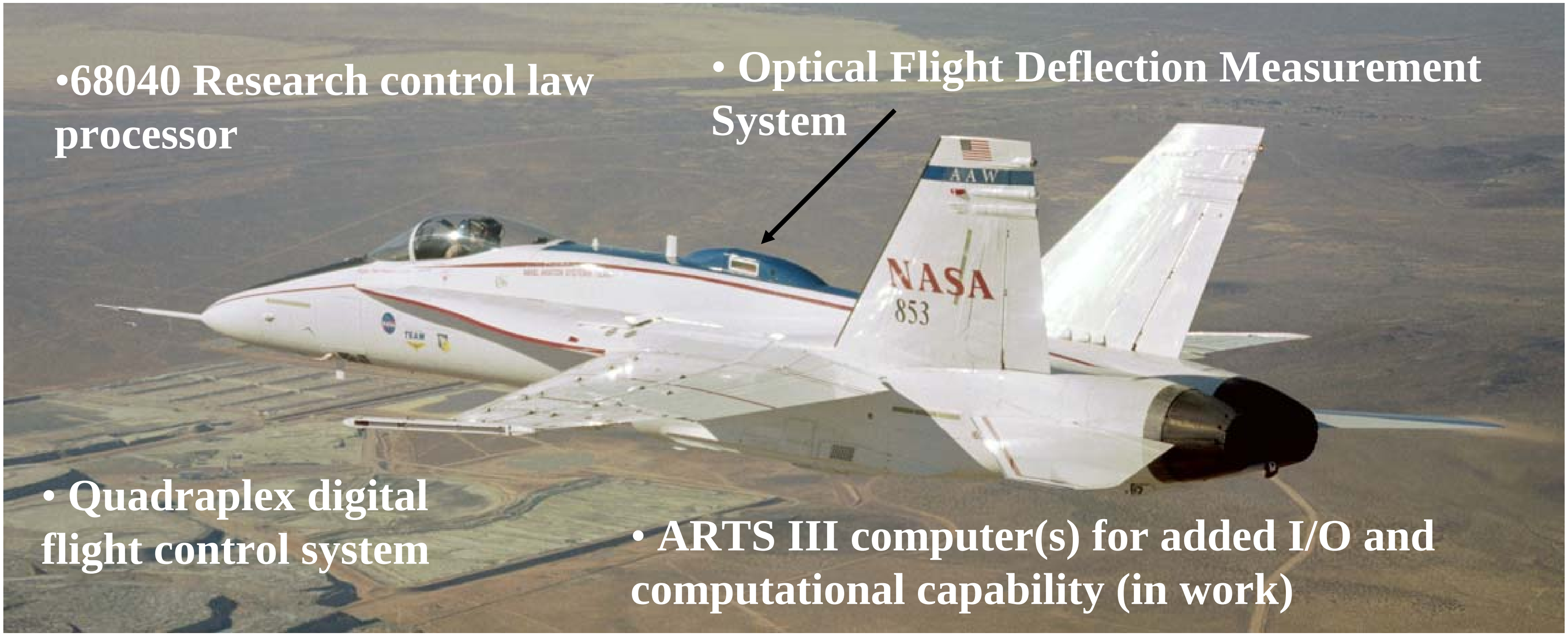
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC96-43479-5 Date: March 22, 1996 Photo by: Dan Murri

F-18 HARV configured with nose strakes during smoke test

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC02-0264-3 Date: November 15, 2002 Photo by: Carla Thomas
The modified F/A-18 being flown in the joint NASA/Air Force Active Aeroelastic Wing research program shows off its colors during its first checkout flight from NASA's Dryden Flight Research Center.

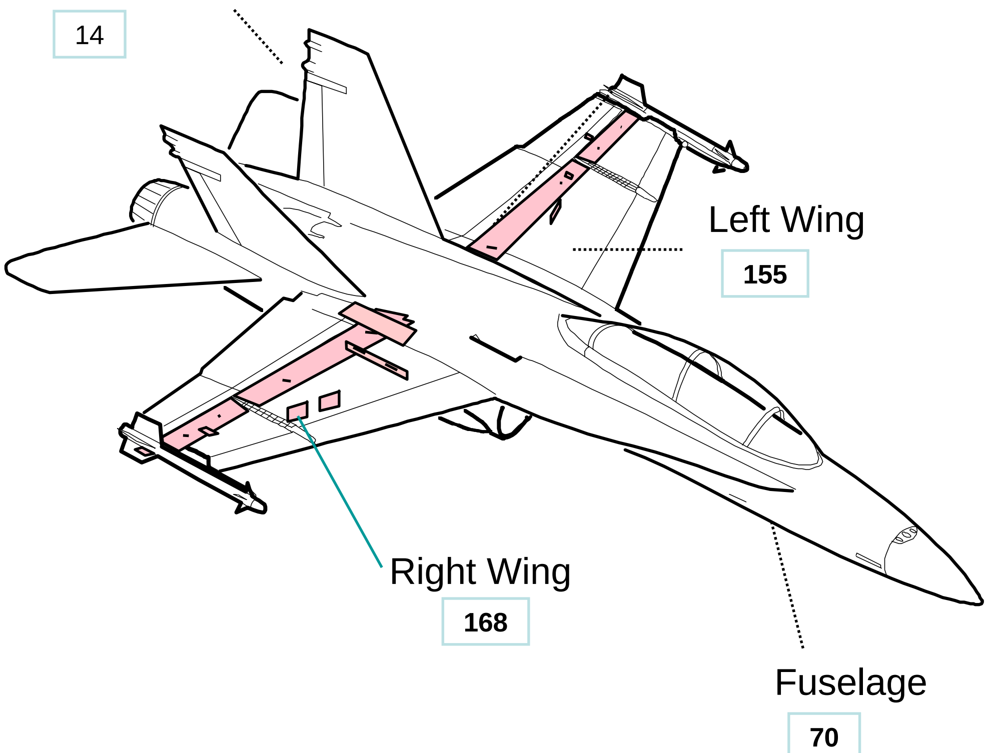
NASA F/A-18 Tail Number 853

Extensively instrumented F/A-18 airframe



Instrumentation

- Sensor by location



RH WING PARAMETERS-168

- **107 - FULL BRIDGE STRAIN GAGES**
- **18 – ACCELEROMETERS**
- **8 – POSITION SENSORS**
- **10 – VOLTAGE SENSORS**
- **3 – TEMPERATURE SENSORS**
- **22 – PRESSURE SENSORS**

LH WING PARAMETERS-155

- **77 - FULL BRIDGE STRAIN GAGES**
- **18 – ACCELEROMETERS**
- **8 – POSITION SENSORS**
- **10 – VOLTAGE SENSORS**
- **4 – TEMPERATURE SENSORS**
- **22 – PRESSURE SENSORS**
- **16 – FDMS TARGETS**

FUSELAGE PARAMETERS-70

- **6 - MOTION PAK**
- **7 – ACCELEROMETERS**
- **7 – TEMPERATURES**
- **8 – FUEL QUANITY**
- **27 – MISC. A/C PARAMETER**
- **15 – TCG PARAMETERS**

EMPONAGE PARAMETERS-14

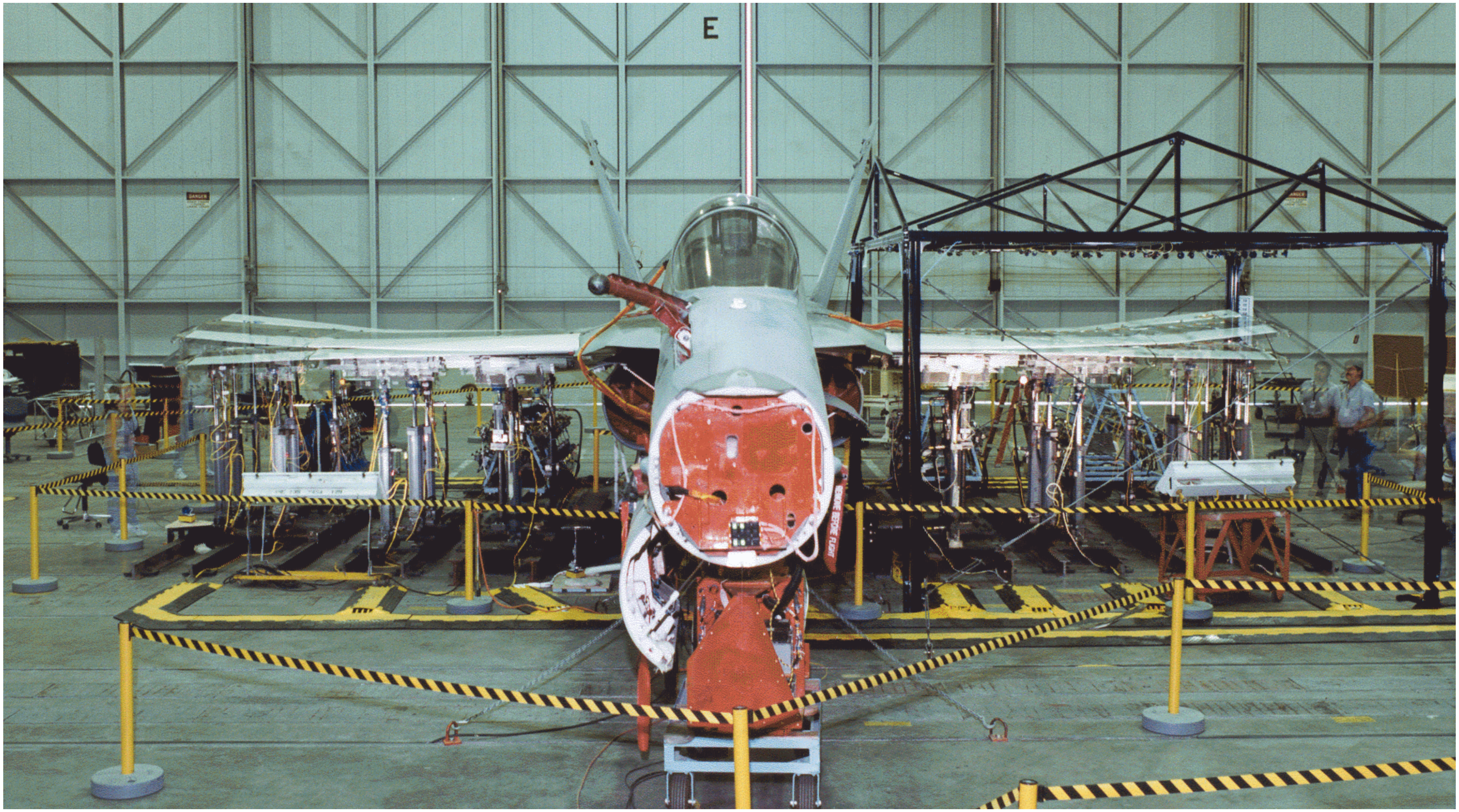
- **4 – POSITIONS SENSORS**
- **10 – ACCELEROMETERS**

A/C 1553 DATA BUS – 1092

GPS/INS 1553 DATA BUS – 170

T0TAL PARAMETERS - 1669

Flight Loads Instrumentation Calibration Test



Near-Term Work to be Completed

- Finalize F/A-18 853 RFCS requirements (Q2 FY08)
- Complete initial RFCS Ada 10.3+ replication control laws and deliver to Boeing (Q2 FY08)
- ARTS III+ feasibility study and development (Q2 FY08 – Q2 FY09)
- F/A-18 RFCS flight experiment PDR (Q4 FY08)
- Complete 68040 1553 and Replication claws task with Boeing (Q2 FY09)
- Continue RFCS trade studies
- F/A-18/generic HIL bench development

Future Work

- Demonstrate integrated adaptive flight and propulsion control and intelligent flight planning in the presence of adverse conditions

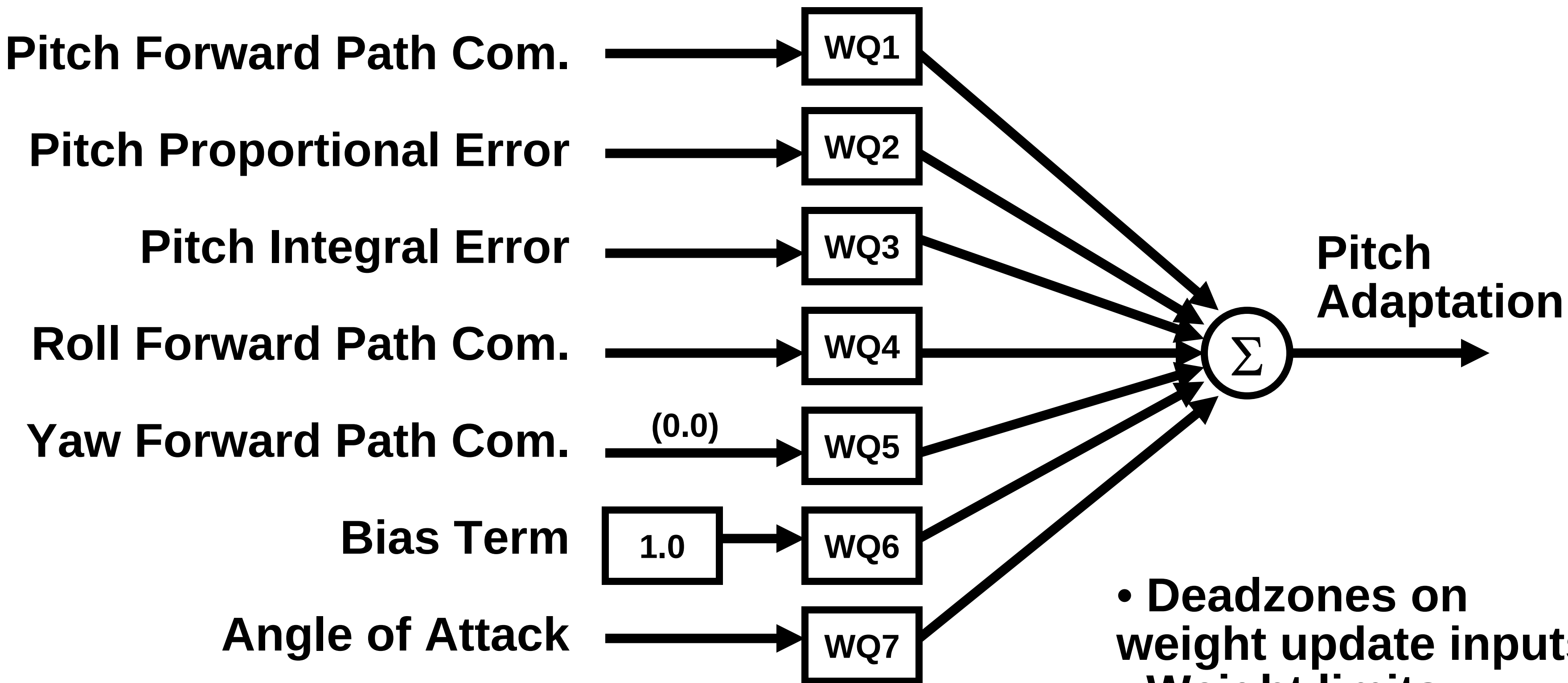
- Incorporate structural feedback and sensed envelope limitations into the adaptive algorithm
  - adaptive notch filters to avoid adverse aero-servo-elastic (ASE) interactions
  - fiber-optic sensor technology

- Develop better metrics – What is most important to ensure that a damaged vehicle can be safely landed?

- Maintain long-term effort to advance numerically-efficient, theoretically-sound adaptive control and control mixer technologies

Back-up slides

Simplified Sigma-Pi Neural Network
Pitch Axis



- Deadzones on weight update inputs
- Weight limits

Weight Update Law: $\dot{W} = -G(U_{err} B_a + L U_{err} W)dt$

Simulated Stabilator Failure

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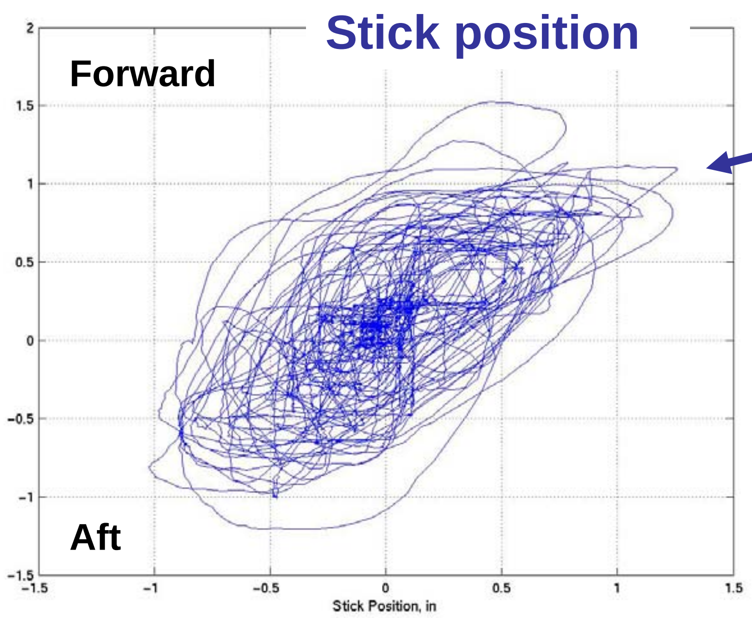
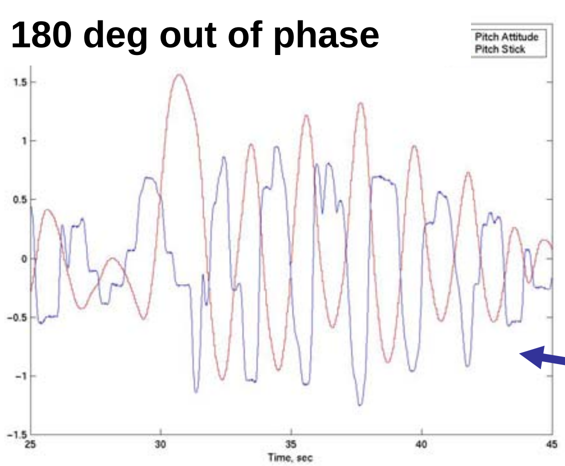
Simulated Frozen Stabilator



- Pilot unconsciously compensates for asymmetry
- Correlated pilot input presents greater challenge for adaptive system



+ Adaptive system reduced the amount of cross coupling

- Adaptive system also introduced tendency for pilot induced oscillations (PIO)

Direct Adaptive Experience and Lessons Learned

- Initial simulation model had high bandwidth
  - Majority of system performance achieved by the dynamic inversion controller
  - Direct adaptive NN played minor role
- Dynamic Inversion gains reduced to meet ASE attenuation requirements
  - Much harder to achieve desired performance
  - NN contribution increased
- Initial performance objective emphasized transient reduction and achieving model following after failure
  - Piloted simulation results showed that reducing cross coupling was more important objective
- Explicit cross terms in NN required for failure cases
  - Relying on disturbance rejection alone doesn't work (also finding of Gen 1)

Direct Adaptive Experience and Lessons Learned

- Liapunov proof of bounded stability
  - Necessary but not sufficient proof of stability (limit cycle behavior observed)
  - Other analytic methods required for ensuring global stability
- Dynamic Inversion controller contributes significantly to cross coupled response in presence of surface failure (locked)
  - Redesigned yaw loop using classical techniques
- NN’s require careful selection of inputs
  - Presence of transient errors “normal” for abrupt inputs in non-adaptive systems
  - Existence of transient errors tend to drive NN’s to “high gain” trying to achieve impossible
- Significant amount of “tuning” required to achieve robust full envelope performance